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Simulating NIF laser-plasma interaction with multiple SRS frequencies

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Abstract. Understanding the energetics of a NIF ignition hohlraum is important to achieving ignition. Laser-plasma interactions (LPI) can reduce the radiation drive if backscatter occurs, and can also affect the hohlraum energetics by modifying the laser beam energy deposition which in turn can alter the implosion symmetry. The addition of a second SRS frequency to the modeling code pF3d can capture physics which would otherwise have been omitted. In the case of a wide or bi-modal SRS spectrum, this physics can be important. We discuss the modifications to the pF3d computational model, and exhibit its effect in a NIF ignition-relevant LPI simulation.

1. Introduction

The National Ignition Facility (NIF) has been designed to achieve fusion ignition in a laboratory setting by imploding a small DT-filled capsule inside a hohlraum. Laser-plasma interactions (LPI) within the hohlraum can have a significant effect on the energetics, thereby altering the symmetry and drive of the capsule implosion. Specifically, diverse mechanisms such as stimulated backscatter, beam spray, beam bending, and beam refraction can all alter the profile of the laser beam's energy deposition, resulting in a modified x-ray conversion. The massively parallel electromagnetic hydrodynamic beam propagation code pF3d ([1, 2, 3]) is used to model LPI within a beam volume inside the hohlraum and calculate the energy deposition along the beam path. This information is then used in hohlraum design simulations to optimize the target design.

For stimulated Brillouin backscatter (SBS), the stimulated light approximately matches the frequency of the incident light. Thus, the light equations can be enveloped around that frequency. For stimulated Raman backscatter (SRS), the reflected light is at a different frequency, thus a specific value must be chosen to calculate the matched SRS light. In the case where the SRS spectrum has one well-defined peak, which is not overly wide (the numerical half-bandwidth of the algorithm is about 10 nm), the choice is clear. For many ignition relevant designs, this has been the case. But there are cases where the choice for a matching frequency is not so clear (see Figure 1, such as a bimodal SRS spectrum, or one which is fairly broad. In this case, the addition of a second frequency enables the simulation to capture the SRS physics matching more of the spectrum.

In the next section, we discuss the computational SRS model and the addition of a second SRS frequency. In the following section, we apply the model to the ignition design with the SRS

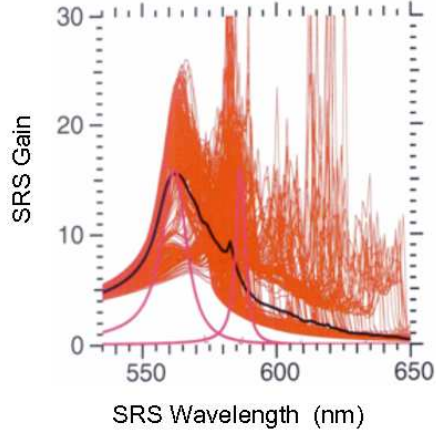


Figure 1. The SRS spectrum for a 285 eV Be-ablator ignition target design. The red curves represent the spectrum for each individual ray used to model the 30° quad of laser beams in the target design, and the black curve is the ray-averaged spectrum. Note this spectrum is not well-matched to a single SRS frequency.

spectrum from Figure 1 and compare the results to a simulation run with only one matching frequency.

2. The computational model

Although stimulated Brillouin scatter (SBS) will be used in the simulations below, its details are not germane to the computational implementation of the SRS. Thus, for simplicity, the SBS model will be excluded here.

The computational model for the light equations follows the paraxial equation. The laser field A_0 is enveloped around the laser frequency and wavenumber ω_0, k_0 ($ck_0(z) = (\omega_0^2 - \bar{\omega}_{pe}^2(z))^{\frac{1}{2}}$) and the SRS field A_R is enveloped around the specified matching frequency ω_R . Adding a second SRS equation primarily consists of adding two more equations to the usual set and modifying the pump wave to add the coupling to the second SRS wave. Using SRS matching frequencies $\omega_{R,j}$ for $j = 1, 2$, the resulting equations are

$$\begin{aligned} \left(\frac{\partial}{\partial t} + v_{g0} \frac{\partial}{\partial z} + \frac{1}{2} v_{g0}' - \frac{ic^2}{2\omega_0} \nabla_{\perp}^2 + \nu_0 - \frac{i}{2\omega_0} \delta\omega^2 \right) \tilde{A}_0 &= -\frac{i}{4} \omega_0 \tilde{A}_{R,1} \frac{\delta n_{l,1}}{n_c} - \frac{i}{4} \omega_0 \tilde{A}_{R,2} \frac{\delta n_{l,2}}{n_c} \\ \left(\frac{\partial}{\partial t} - v_{gR,j} \frac{\partial}{\partial z} + \frac{1}{2} v_{gR,j}' - \frac{ic^2}{2\omega_{R,j}} \nabla_{\perp}^2 + \nu_{R,j} - \frac{i}{2\omega_{R,j}} \delta\omega^2 \right) \tilde{A}_{R,j} &= -\frac{i}{4} \frac{\omega_0^2}{\omega_{R,j}} \tilde{A}_0 \frac{\delta n_{l,j}^*}{n_c} \end{aligned}$$

where $\delta\omega^2 = \omega_{pe}^2 - \bar{\omega}_{pe}^2$. The Langmuir density $\delta n_{l,j}$ is enveloped around $\omega_0 - \omega_{R,j}$,

$$\left(\frac{\partial}{\partial t} - v_{gl,j} \frac{\partial}{\partial z} - \frac{3iv_e^2}{2\omega_{l,j}} \nabla_{\perp}^2 + \nu_{l,j} + i\Delta_{l,j} \right) \frac{\delta n_{l,j}}{n_c} = -\frac{i\omega_{pe}^2 k_{l,j}^2}{4\omega_{l,j}\omega_0^2} \left(\frac{e\tilde{A}_0}{m_e c} \right) \left(\frac{e\tilde{A}_{R,j}^*}{m_e c} \right) \mathcal{F}_j.$$

where $\Delta_{l,j}$ is the spatially dependent mismatch. The multipliers $\mathcal{F}_j = \mathcal{F}_j(n_e, T_e)$ are chosen to be spatially disjoint (point-wise) $\{x : \mathcal{F}_1(x) \neq 0\} \cap \{x : \mathcal{F}_2(x) \neq 0\} = \emptyset$ to prevent a single spatial location from providing a source term to more than one SRS wave. Action is conserved point-wise via

$$\begin{aligned} \frac{\partial}{\partial t} A_0 &= -i \sum_{j \neq 0} c_j A_{R,j} \quad \text{and} \quad \frac{\partial}{\partial t} A_{R,j} = -i c_j^* A_0 \\ &\quad \text{with} \\ A_0 &= -2\sqrt{\omega_0} \tilde{A}_0 \\ A_{R,j} &= -2\sqrt{\omega_{R,j}} \tilde{A}_{R,j} \quad c_j = -\frac{\omega_{pe}^2 \omega_{R,j}}{4\sqrt{\omega_0 \omega_{R,j}}} \end{aligned}$$

which gives

$$|\tilde{A}_0(t)|^2 + |\tilde{A}_{R,1}(t)|^2 + |\tilde{A}_{R,2}(t)|^2 = \text{const.}$$

We have found this approach to work well for well-separated peaks in a Raman spectrum. For closely located peaks, simulations are performed using only one SRS matching frequency.

3. Applying the model to an ignition target

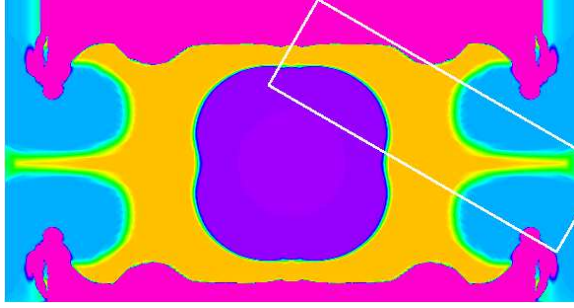


Figure 2. The material plot for a 285 eV Be-ablator ignition target design at peak power. Shown are the pink high- Z hohlraum wall, the blue CH LEH liner, the orange H_4He fill gas and the purple Be ablator. The white rectangle shows the radial projection of the simulation volume.

The target design shown in Figure 2 has significant gain at different densities (c.f. Figure 1), and hence is a good candidate for a two-group simulation. We first performed a near whole beam simulation over the entire beam path length. The full radial extent of the beam was included, but the azimuthal extent was reduced to a subset just large enough to provide adequate beam statistics. Only one matching SRS frequency (at 562 nm) was used. This single SRS group simulation was run on 4,096 (AMD Opteron) processors for approximately ten days before reaching a steady state (~ 100 ps). Slicing planes aligned with the hohlraum radius through the 3D plasma volume are shown in Figure 3 which have been taken as time averages over 25 ps at steady state. The laser propagation direction is vertical, bottom to top. At the upper left corner

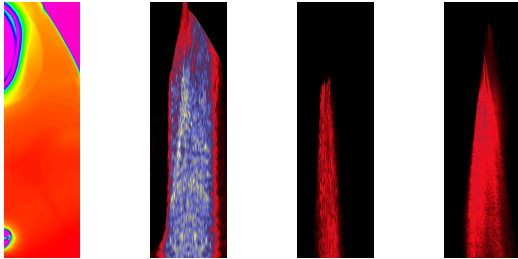


Figure 3. (left to right) Whole beam electron density normalized to $0.8 n_{\text{crit}}$. Laser intensity, SBS intensity, and SRS intensity normalized to $8 \times 10^{14} \text{ W/cm}^2$.

of the density plot is the capsule ablator plasma, and at the upper right is the hohlraum wall. The feature in the lower left corner is the lip of the laser-entrance-hole (LEH). The incoming laser intensity refracts away from the higher density blowoff from the expanding lip liner as it propagates into the hohlraum. The SBS amplifies in the ablator plasma (left-hand side of the plot), and the SRS in the fill gas closer to the hohlraum wall (right-hand side of the plot).

Performing the same near whole beam simulation with the addition of the second SRS matching frequency (at 587 nm) reveals a slightly different story. The two-group simulation took about 20% longer on 4,096 cpus to reach ~ 100 ps. Averaging over 25 ps at steady state (Figure 4), we find some of the energy which went into SBS in the prior simulation now goes into the alternate SRS wave. This observation is consistent with the reflectivity plots, depicted in Figure 5. The SBS level is higher in the one-group simulations than the two-group calculation. The SRS reflectivity which matches 562 nm is unchanged between the two runs, but the SRS reflectivity of the 587 nm light comes in around 1.5%, which is almost the amount of decrease in the SBS.

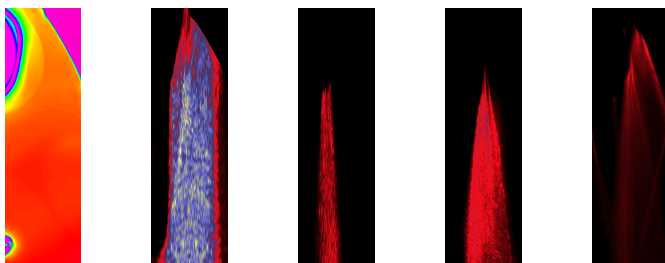


Figure 4. (left to right) Whole beam electron density normalized to $0.8 n_{crit}$. Laser intensity SRS intensity, and alternate SRS intensity normalized to $8 \times 10^{14} \text{ W/cm}^2$.

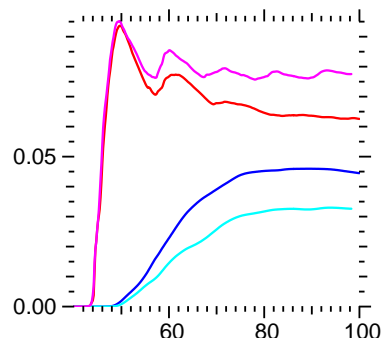


Figure 5. Comparison between the two simulations of reflectivity as a fraction of input intensity versus time [ps]. 1-group: SBS=cyan and SRS=magenta; 2-group: SBS=blue and SRS=red.

4. Conclusions

For target designs in which there is more than one SRS matching region, performing a simulation using a second SRS matching frequency captures physical effects that would have otherwise been overlooked. As a proof-of-principle, we have implemented the two-group model in the current pF3d beam propagation code, and performed comparison LPI simulations of a specific NIF ignition-relevant target. We found the single-group simulation overpredicts the SRS reflectivity compared to the two-group calculation, and the difference in energy goes into the second SRS wave. We have now begun to routinely apply the new code to analyze NIF ignition and ignition-emulator targets.

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